

Evidence for a 304-day Orbital Period for GX 1+4

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Abstract. In this paper we report strong evidence for a ~ 304 -day periodicity in the spin history of the accretion-powered pulsar GX 1+4 that is very likely to be a signature of the orbital period of the system. Using BATSE public-domain data, we show a highly-significant periodic modulation of the pulsar frequency from 1991 to date which is in excellent agreement with the ephemeris proposed by Cutler, Dennis & Dolan in 1986 [1], which were based on a few events of enhanced spin-up that occurred during the pulsar's spin-up era in the 1970s. Our results indicate that the orbital period of GX 1+4 is 303.8 ± 1.1 days, making it by far the widest low-mass X-ray binary system known. A likely scenario for this system is an elliptical orbit in which the neutron star decreases its spin-down rate (or even exhibits a momentary spin-up behavior) at periastron passages due to the higher torque exerted by the accretion disk onto the magnetosphere of the neutron star.

INTRODUCTION

GX 1+4 is a unique accretion-powered pulsar in a low-mass x-ray binary system (LMXB). In the 1970s the pulsar exhibited a spin-up behavior with a rate of $\dot{P} \sim -2$ s/year, the highest among all persistent X-ray pulsars, and was one of the brightest and hardest X-ray sources in the sky. After an extended low-intensity state in the early 1980s, GX 1+4 re-emerged in a spin-down state [2] and has produced occasional short-term variations of \dot{P} ever since. The optical counterpart is a M5 III giant star, V2116 Oph, in a rare type of symbiotic system [3–5]. The identification was made secure by a ROSAT accurate position [6] and by the discovery of optical pulsations consistent with the spin period of the neutron star [7,8]. In 1991, BATSE initiated a continuous and nearly uniform monitoring of GX 1+4, confirming the spin-down trend with occasional dramatic spin-up/down torque reversal events [9,10]. GX 1+4 has a much longer (factor of ~ 100) spin period than the other four known LMXB accretion-powered pulsars and its orbital period has been known to be at least one order of magnitude longer than the periods of the other systems [5]. Attempts to find the orbital period by Doppler shifts of the pulsar pulse timing [9] or optical lines [4,11,12] have both been inconclusive

so far. Using a small number of X-ray measurements carried out during the spin-up phase of GX 1+4 in the 1970s, Cutler, Dennis & Dollan [1] produced an ephemeris for predicting periodical enhancements in the spin-up rate of the neutron star and claimed that this could be due to an elliptical orbit with a 304-day period. Here we report the discovery of a 304-day modulation in the BATSE frequency data and discuss its implications to the models for this source.

DATA ANALYSIS AND RESULTS

The frequency and the pulsed flux data between Julian Day (JD) 2448376.5 and 2451138.5 (i.e., 1991 April 29 to 1998 October 20) used in this work were obtained from Chakrabarty [9] and from the BATSE public domain data. The 20–50 keV pulsed signals are extracted from DISCLA 1.024s channel 1 data. 15-day mean values for the fluxes and pulse frequencies of GX 1+4 were calculated for the entire dataset.

A dataset of GX 1+4 residual pulsation frequencies was obtained from the frequency history by subtraction of a standard cubic spline function to remove low frequency variations in the spin-down trend. The fitting points are mean frequency values calculated over suitably chosen time intervals. The results of the spline fitting are fairly insensitive to intervals greater than ~ 200 days between fitting points (we have used $\Delta t = 215$ days). The pulsed X-ray flux, frequency history and residual frequencies are shown in Figure 1 as functions of time.

We have carried out a power spectrum analysis to search for periodicities of less than 1000 days in both the residual frequency and the pulsed flux data. A Lomb-Scargle periodogram [13], suitable for time series with gaps, shows a significant periodic signal at 302.0 days (Fig. 2) in the residual frequency time series. The power spectrum shows a red noise with an approximate power-law index of -2 . In order to estimate the statistical significance of the detection, a series of numerical simulations of the frequency time series with 1-sigma gaussian deviations were performed [14]. The simulations show that the use of the 215-d spline, besides providing an effective filter for frequencies below $\sim 2 \times 10^{-3} \text{d}^{-1}$, does not produce power in any specific frequency in the range of interest. By comparing the amplitude of our 302-day peak with the local value obtained by the mean of the numerical simulations, we obtain a statistical significance of 99.98% for the detection. Epoch folding the data using the 302-day period yields a $1\text{-}\sigma$ uncertainty of 1.7 days.

By analyzing the variation of the period of GX 1+4 during the spin-up phase in the 1970s, Cutler, Dennis & Dolan [1] proposed a 304-day orbital period and an ephemeris to predict the events of enhanced spin-up: $T = \text{JD } 2,444,574.5 \pm 304 n$, where n is an integer. This ephemeris is based on four events discussed by the authors, whose existence was inferred from ad-hoc assumptions and extrapolations of the observations. The projected enhanced spin-up events derived from that ephemeris for the epochs contained in the BATSE dataset, represented as solid vertical lines in the lower panel of Fig. 1, are in excellent agreement with

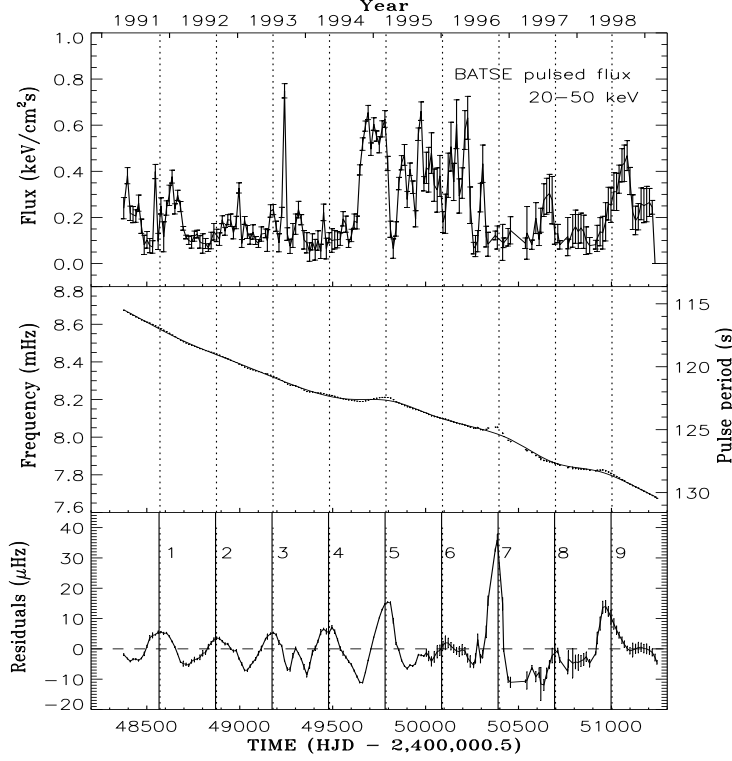


FIGURE 1. *Upper panel:* Light curve of the 20-50 keV pulsed flux of GX 1+4 as measured by BATSE from 1991 to 1998; *middle panel:* GX 1+4 frequency measurements by BATSE over the same period. The error bars are in general smaller than the size of the dots. The solid curve is a cubic spline fit to the data; *lower panel:* frequency residuals. The dotted vertical lines mark the times times predicted by the ephemeris calculated in this work, whereas the solid vertical lines show the predictions of Cutler, Dennis & Dolan (1996). The events of positive residual frequency modulation are labeled for reference in the text.

the BATSE reduced spin-down and spin-up events. The BATSE dataset is obviously significantly more reliable than the one given by Cutler, Dennis & Dolan [1] since it is based on 9 well-covered events measured with the same instrument as opposed to the 4 events discussed by those authors. The striking agreement of their ephemeris with the BATSE observations is very conspicuous and give a very strong support to the claim that the orbital period of the system is indeed ~ 304 days. Taking integer cycle numbers, with the T_0 epoch of Cutler, Dennis & Dolan [1] as cycle -23 , and performing a linear least-squares fit to the frequency residuals seen in the lower panel of Fig. 1, we find that the following ephemeris can represent the time of occurrence T of the maxima in the frequency residuals: $T = \text{JD } 2,448,571.3(\pm 3.2) \pm 303.8(\pm 1.1) n$, where n is any integer. The events predicted by the above ephemeris are shown as vertical dotted lines in the three panels of Fig. 1. The value of 303.8 ± 1.1 days for the orbital period is consistent

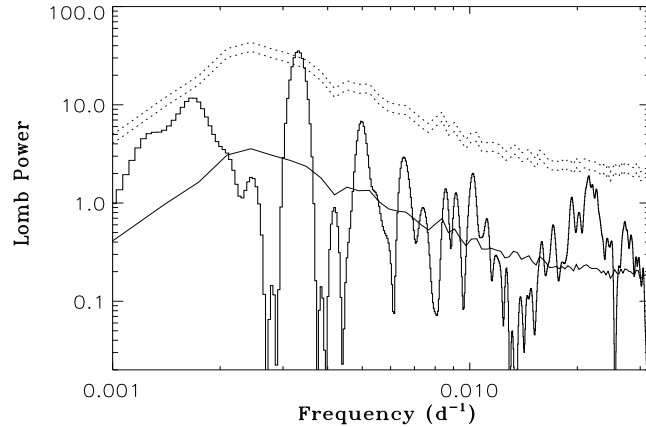


FIGURE 2. Lomb-Scargle periodogram of the frequency residuals of GX 1+4 from 1991 to 1998, represented by the histogram-type solid line. The standard solid line is the mean of 1500 numerical simulations carried out in order to calculate the significance level of the detection. The upper dotted line indicates a significance level of 0.001, whereas the lower dotted line indicates a significance level of 0.01.

with the one obtained through power spectrum analysis performed on the BATSE data, which gives further support for the period determination.

DISCUSSION

In the 1970s, when the measurements used by Cutler, Dennis & Dolan [1] were carried out, the source was in a spin-up extended state. They proposed that the periodic occurrence of enhanced spin-up events was due to the fact that the system was in a elliptical orbit and the periastron passages would occur when \dot{P} is maximum, as expected in standard accretion from a spherically expanding stellar wind. However, it is widely accepted today that the system has an accretion disk. Since the neutron star is currently spinning-down, the radius at which the magnetosphere boundary would corotate with the disk is probably smaller than the magnetosphere radius. Since the pulse period is ~ 120 s and the luminosity is typically $\lesssim 10^{37}$ erg/s, it can be shown [14] that the period is probably close to the equilibrium value, for which the two radii are equal. This allows spin-down to occur even though accretion continues, the centrifugal barrier not being sufficiently effective [15]. Assuming that the elliptical orbit is the correct interpretation for the presence of the modulation, the mass accretion rate (and hence the luminosity) should increase as the neutron star approaches periastron. The spin-down torque then gets smaller and the neutron star decelerates at a slower rate [14]. Occasionally, due to the highly variable mass loss rate of the red giant, the neutron star will *spin-up* for a brief period of time during periastron, as observed in

the BATSE frequency curve in events 5, 7 and 9. According to this picture, one would expect an increase in X-ray luminosity at periastron. Although this is only marginally indicated in the BATSE pulsed flux light curve, it should be pointed out that total flux data from the ASM/RXTE for the epoch MJD 50088 to 51044 does not correlate significantly with the BATSE pulsed flux, indicating that the pulsed flux may not be a good tracer of the accretion luminosity in this system. Furthermore, the periodic $\sim 5\mu\text{Hz}$ excursions in the residual frequency would lead to very low-significance variations in the X-ray flux measured by the ASM [14].

An alternative interpretation for the observed modulation would be the presence of oscillation modes in the red giant star. However, the stability of the infrared magnitudes of V2116 Oph [5] preclude it from being a long-period variable, since these stars undergo regular $\gtrsim 1$ mag variations in the infrared [16].

We conclude by pointing out that, given the 304-day orbital period and the spectral and luminosity characteristics of V2116 Oph, it can be shown that the companion in this system is probably not filling its Roche lobe and the accretion disk forms from the slow, dense stellar wind of the red giant [14]. A more thorough covering of the X-ray luminosity of the system, with high sensitivity and spanning several cycles, will be very important to test the elliptical model for GX 1+4.

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